High-frequency-peaked BL Lacertae objects
as spectral candles to measure
the Extragalactic Background Light
in the Fermi and air Cherenkov telescopes era

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ABSTRACT

The Extragalactic Background Light (EBL) is the integrated light from all the stars that have ever formed, and spans the IR-UV range. The interaction of very-high-energy (VHE: $E > 100\,\mathrm{GeV}$) γ-rays, emitted by sources located at cosmological distances, with the intervening EBL results in $e^{-}e^{+}$ pair production that leads to energy-dependent attenuation of the observed VHE flux. This introduces a fundamental ambiguity in the interpretation of measured VHE γ-ray spectra: neither the intrinsic spectrum, nor the EBL, are separately known – only their combination is. In this paper we propose a method to measure the EBL photon number density. It relies on using simultaneous observations of BL Lac objects in the optical, X-ray, high-energy (HE: $E > 100\,\mathrm{MeV}$) γ-ray (from the Fermi telescope), and VHE γ-ray (from Cherenkov telescopes) bands. For each source, the method involves best-fitting the spectral energy distribution (SED) from optical through HE γ-rays (the latter being largely unaffected by EBL attenuation as long as $z \lesssim 1$) with a Synchrotron Self-Compton (SSC) model. We extrapolate such best-fitting models into the VHE regime, and assume they represent the BL Lacs' intrinsic emission. Contrasting measured versus intrinsic emission leads to a determination of the $\gamma\gamma$ opacity to VHE photons. Using, for each given source, different states of emission will only improve the accuracy of the proposed method. We demonstrate this method using recent simultaneous multi-frequency observations of the high-frequency-peaked BL Lac object PKS 2155-304 and discuss how similar observations can more accurately probe the EBL.

Subject headings: BL Lacertae objects: general – BL Lacertae objects: individual (PKS 2155-304) – diffuse radiation – gamma rays: galaxies – infrared: diffuse background

1. Introduction

The Extragalactic Background Light (EBL), in both its level and degree of cosmic evolution, reflects the time integrated history of light production and re-processing in the Universe, hence the history of cosmological star-formation. Roughly speaking, its shape must reflect the two humps that characterize the spectral energy distributions (SEDs) of galaxies: one arising from starlight and peaking at $\lambda \sim 1\,\mu$m (optical background), and one arising from warm dust emission and peaking at $\lambda \sim 100\,\mu$m (infrared background). However, direct measurements of the EBL are hampered by the dominance of foreground emission (interplanetary dust and Galactic emission), hence the level of EBL emission is uncertain by a factor of several.

One approach to evaluate the EBL emission level has been modeling the integrated light that arises from an evolving population of galactic stellar populations. However, uncertainties in the assumed galaxy formation and evolution scenarios, stellar initial mass function, and star formation rate have led to significant discrepancy among models (e.g., Salamon & Stecker 1998; Malkan & Stecker 1998 and Stecker & de Jager 1998; Kneiske et al. 2002 and 2004; Stecker, Malkan & Scully 2006; Razzaque, Dermer & Finke 2009 and Finke, Razzaque & Dermer 2010). These models have been used to correct observed VHE spectra and deduce (EBL model dependent) 'intrinsic' VHE γ-ray emissions.

The opposite approach, of a more phenomenological kind, deduces upper limits on the level of EBL attenuation making basic assumptions on the intrinsic VHE γ-ray shape of AGN spectra. Specifically, it was assumed that the latter are described by a power-law photon index $\Gamma \geq 1.8$ (Schroedter 2005), $\Gamma \geq 1.5$ (e.g., Aharonian et al. 2006; Mazin & Goebel 2007; Mazin & Raue 2007), and $\Gamma \geq 1$ (Finke & Razzaque 2009). These assumptions correspond to various possibilities of producing TeV spectra. Shock-accelerated electrons are unikely to produce VHE γ-rays with $\Gamma < 1.5$ from Compton scattering (e.g., Blandford & Eichler 1987). However, either internal $\gamma\gamma$ absorption (Aharonian et al. 2008), or harder electron spectra at the highest

energies in relativistic shocks (Stecker, Baring & Summerlin 2007), or Compton scattering of CMB photons (Böttcher et al. 2008), or top-heavy power-law energy distributions of the emitting electrons (Katarzynski et al. 2006) could lead to harder intrinsic TeV spectra – not to mention that pion decay from a hadronic source would produce a very hard TeV component, irrespective of the lower-energy electron synchrotron spectrum (Mücke et al. 2003). Another proposed approach to derive EBL upper limits involves assuming that a same-slope extrapolation of the observed *Fermi*/LAT HE spectrum into the VHE domain exceeds the intrinsic VHE spectrum there (Georganopulos, Finke & Reyes 2010). An approach to exploring the redshift evolution of the EBL exploits the GeV-TeV connection for blazar spectra (Stecker & Scully 2010).

A different, but related, approach to constraining the EBL rests on evaluating the collective blazar contribution to the extragalactic γ-ray background when the inescapable electromagnetic cascades of lower-energy photons and electrons, initiated by the interaction of VHE photons with the EBL, are accounted for. The collective intensity of a cosmological population of VHE γ-ray sources will be attenuated at the highest energies through interaction with the EBL and enhanced at lower energies by the resulting cascade: the strength of the effect depends on the source γ-ray luminosity function and spectral index distribution, and on the EBL model (Venters 2010). The extragalactic γ-ray background, resulting from the contributions of different classes of blazars, can then be used to constrain the EBL (Kneiske & Mannheim 2008; Venters, Pavlidou & Reyes 2009) – even though the amount of energy flux absorbed and reprocessed is probably only a small fraction of the total extragalactic γ-ray background energy flux (Inoue & Totani 2009).

The only unquestionable constraints on the EBL are model-independent lower limits based on galaxy counts (Dole et al. 2006; Franceschini, Rodighiero & Vaccari 2008). It should be noted, however, that the EBL upper limits in the 2–80μm obtained by Mazin & Raue (2007) combining results from all known TeV blazar spectra (based on the assumption that the intrinsic $\Gamma \geq 1.5$) are only a factor $\approx$2–2.5 above the absolute lower limits from source counts. So it would appear

that there is little room for additional components like Pop III stars (Raue, Kneiske & Mazin 2009; Aharonian et al. 2006), unless we miss some fundamental aspects of blazar emission theory (which have not been observed in local sources, however).

An attempt to measure the EBL used the relatively faraway blazar 3C 279 as a background light source (Stecker, de Jager & Salamon 1992), assuming that the intrinsic VHE spectrum was known from extrapolating an apparently perfect E^{-2} power-law differential energy spectrum, known in the interval from 70 MeV to >5 GeV from EGRET data, by a couple of further decades in energy into the VHE regime. However, blazars are highly variable sources, so it's almost impossible to determine with confidence the intrinsic TeV spectrum – which itself can be variable.

In this paper we propose a method to measure the EBL that improves on Stecker et al. (1992) by making a more realistic assumption on the intrinsic TeV spectrum. Simultaneous optical/X-ray/HE/VHE (i.e., eV/keV/GeV/TeV) data are crucial to this method, considering the strong and rapid variability displayed by most blazars. After reviewing features of EBL absorption (sect. 2) and of the adopted BL Lac emission model (sect. 3), in sect. 4 we describe our technique, in sect. 5 we apply it to recent multifrequency observations of PKS 2155-304 and determine the $\gamma\gamma$ optical depth out to that source's redshift. In sect. 6 we discuss our results.

2. EBL absorption

The cross section for the reaction $\gamma\gamma \rightarrow e^+ e^-$ is

$$\sigma_{\gamma\gamma}(E, \epsilon, \phi) = \frac{3}{16} \sigma_{\mathrm{T}} (1 - \beta^2) \times$$
$$\times \left[2\beta(\beta^2 - 2) + (3 - \beta^4) \ln\frac{1+\beta}{1-\beta} \right] \quad (1)$$

(see Stecker et al. 1992), where σ_{T} is the Thompson cross section and $\beta(E, \epsilon, \phi) \equiv \sqrt{1 - 2(m_e c^2)^2 / E\epsilon(1 - \cos\phi)}$ with ϕ the angle between the photons of energy, respectively, E ('hard') and ϵ ('soft').

Purely for analytical demonstration purposes we assume, following Stecker et al. (1992), that $n_{EBL}(\epsilon) \propto \epsilon^{-2.55}$ is the local number density of EBL photons having energy equal to ϵ as appropriate in the mid- to far-infrared ($\sim$20-100 μm) range [1] (no redshift evolution – as befits the relatively low redshifts currently accessible to Cherenkov telescopes), z_s is the source redshift, and the cosmology is flat no-Λ ($\Omega_0 = 1$) [2]. The optical depth due to pair-creation attenuation between the source and the Earth,

$$\tau_{\gamma\gamma}(E, z_s) = \frac{c}{H_0} \int_0^{z_s} \sqrt{1+z} \, dz \int_0^2 \frac{x}{2} dx \ \times$$
$$\times \int_{\frac{2(m_e c^2)^2}{Ex(1+z)^2}}^{\infty} n_{EBL}(\epsilon) \ \sigma_{\gamma\gamma}(2xE\epsilon(1+z)^2) \ d\epsilon \tag{2}$$

where $x \equiv (1 - \cos\phi)$ and H_0 being the Hubble constant, turns out to be $\tau_{\gamma\gamma}(E, z) \propto E^{1.55} z_s^{\eta}$ with $\eta \sim 1.5$.

This calculation, although it refers to an idealized case, highlights an important property of the VHE flux attenuation by the $\gamma_{VHE}\gamma_{EBL} \to e^+ e^-$ interaction: $\tau_{\gamma\gamma}$ depends both on the distance traveled by the VHE photon (hence on z) and on the photon's (measured) energy E. So the spectrum measured at Earth is distorted with respect to the emitted spectrum. In detail, the expected VHE γ-ray flux at Earth will be: $F(E) = (dI/dE) \, e^{-\tau_{\gamma\gamma}(E)}$ (differential) and $F(>E) = \int_E^{\infty} (dI/dE') \, e^{-\tau_{\gamma\gamma}(E')} dE'$ (integral).

3. BL Lac SSC emission

In order to reduce the degrees of freedom, we use a simple one-zone SSC model (for details see Tavecchio, Maraschi & Ghisellini 1998, and Tavecchio & Maraschi 2003). This has been

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[1] The EBL has a two-bump spectral shape, and does not follow a simple power law but a polynomial of higher order.

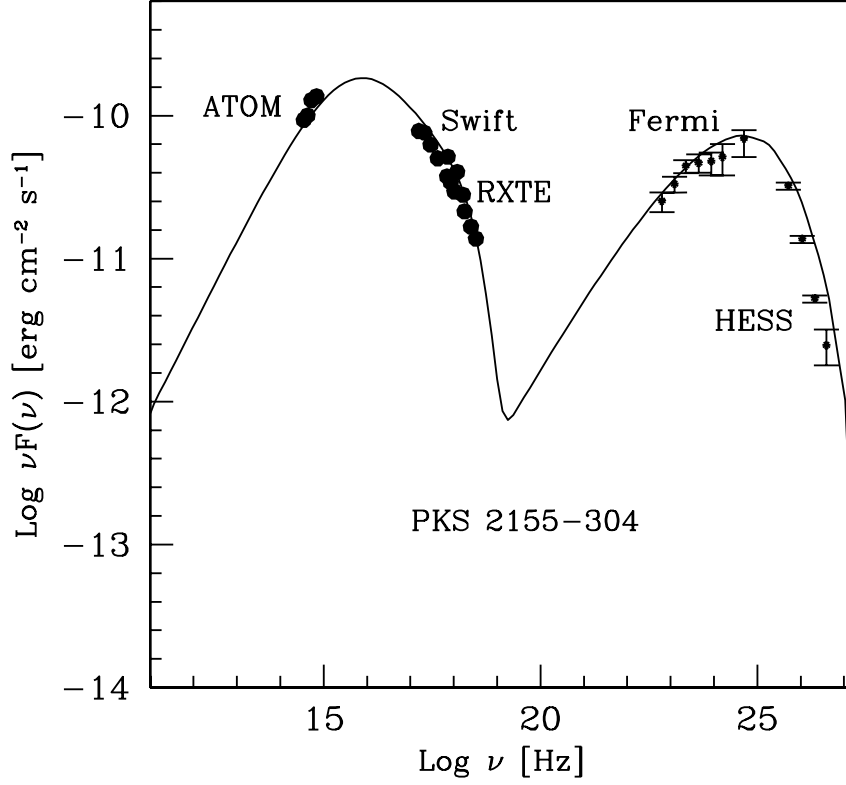[2] The main result does not change if the currently favored concordance cosmology is used.

Fig. 1.— Data (symbols: from Aharonian et al. 2009; no VHE γ-ray upper limits reported) and best-fit one-zone SSC model (solid curve) of the SED of PKS 2155-304. The best-fit ($\chi^2_\nu = 0.78$ for $\nu = 16$ degrees of freedom) SSC parameters are: $n_e = 150\,\mathrm{cm}^{-3}$, $\gamma_{\mathrm{br}} = 2.9 \times 10^4$, $\gamma_{\mathrm{max}} = 8 \times 10^5$, $\alpha_1 = 1.8$, $\alpha_2 = 3.8$, $R = 3.87 \times 10^{16}\,\mathrm{cm}$, $\delta = 29.2$, $B = 0.056\,\mathrm{G}$. The obtained values of R and δ imply a variability timescale $t_{\mathrm{var}} \sim R\,(1+z)/(c\delta)$, which is compatible with the observed value of $\approx 12\,\mathrm{hr}$.

shown to adequately describe broad-band SEDs of most high-frequency-peaked BL Lac objects (HBLs; e.g., Ghisellini et al. 1998) and, for a given source, both its ground and excited states (Tavecchio et al. 2001; Tagliaferri et al. 2008). The main support for the one-zone model is that in most such sources the temporal variability is clearly dominated by one characteristic timescale, which implies one dominant characteristic size of the emitting region (e.g., Anderhub et al. 2009). Moreover, one of the most convincing evidence favouring the SSC model is the strict correlation between the variations in the X-ray and in the TeV band (e.g., Fossati et al. 2008). Since in the SSC model the emission in the two bands is produced by the same electrons (via synchrotron and SSC mechanism, respectively), a strict correlation is expected. However, there are (rare) exceptions, e.g. the so-called "orphan" TeV flares (Krawczynski et al. 2004) which are not accompanied by corresponding variations in the X-ray band; or more complex models than the simple one-zone SSC model may be required to fit the observed variability pattern in some cases (e.g., the July 2006 flare of PKS 2155-304: see Costamante 2008; but also Foschini et al. 2007 and Kusunose & Takahara 2008).

The emission zone is supposed to be spherical with radius R, in relativistic motion with bulk Lorentz factor Γ at an angle θ with respect to the line of sight to the observer, so that special relativistic effects are cumulatively described by the relativistic Doppler factor, $\delta = [\Gamma(1 - \beta \cos \theta)]^{-1}$. Relativistic electrons with density $n_{\rm e}$ and a tangled magnetic field with intensity B homogeneously fill the region. The relativistic electrons' spectrum is described by a smoothed broken power-law function of the electron Lorentz factor γ, with limits γ_1 and γ_2 and break at $\gamma_{\rm br}$ and low- and high-energy slopes α_1 and α_2. This purely phenomenological choice is motivated by the observed shape of the bumps in the SEDs, well represented by two smoothly joined power laws. In calculating the SSC emission we use the full Klein-Nishina cross section, especially important in shaping the TeV spectrum.

As detailed in Tavecchio et al. (1998), this simple model can be fully constrained by using

simultaneous multifrequency observations. Indeed, the model's free parameters are 9, of which 6 specify the electron energy distribution (n_e, γ_1, γ_{br}, γ_2, α_1, α_2), and 3 describe the global properties of the emitting region (B, R, δ). On the other hand, from observations ideally one can derive 9 observational quantities: the slopes of the synchrotron bump after and above the peak $\alpha_{1,2}$ (uniquely connected to $n_{1,2}$), the synchrotron and SSC peak frequencies ($\nu_{s,C}$) and luminosities $L_{s,C}$, and the minimum variability timescale t_{var} which provides an estimate of the size of the sources through $R < ct_{var}\delta/(1+z)$.

Therefore, once the relevant observational quantities are known, one can uniquely derive the set of SSC parameters.

4.   The method

The method we are proposing stems from the consideration that both the EBL and the intrinsic VHE γ-ray spectra of background sources are fundamentally unknown. In order to measure the EBL at different z, one should single out a class of sources that is homogeneous, i.e. it can be described by one same emission model at all redshifts. This approach is meant to minimize biases that may possibly arise from systematically different SED modelings adopted for different classes of sources at different distances. So we choose the class of source that has both a relatively simple emission model and the potential of being seen from large distances: BL Lac objects, i.e. AGNs whose relativistic jets point directly toward the observer so their luminosities are boosted by a large factor and dominate the source flux with their SSC emission. Within BL Lacs, we propose to use the sub-class of HBL, because their Compton peak can be more readily detected by Cherenkov telescopes than other types of source, and because their HE spectrum can be described as a single (unbroken) power law in photon energy, unlikely other types of BL Lacs (Abdo et al. 2009).

For a given BL Lac, our method relies on using, a simultaneous broad-band SED that samples the optical, X-ray, high-energy (HE: $E > 100\,\mathrm{MeV}$) γ-ray (from the *Fermi* telescope), and VHE γ-ray (from Cherenkov telescopes) bands. A given SED will be best-fitted, from optical through HE γ-rays, with a Synchrotron Self-Compton (SSC) model. [Photons with $E \lesssim 100\,\mathrm{GeV}$ are largely unaffected by EBL attenuation (for reasonable EBL models) as long as $z \lesssim 1$.] Extrapolating such best-fitting SED model into the VHE regime, we shall assume it represents the source's intrinsic emission. It should be emphasized that the electrons that are responsible for such "intrinsic" VHE emission are the same that have been simultaneously and cospatially measured through their synchrotron emission in the optical and X-ray bands and the Compton emission in the HE γ-ray band. As emphasized by Coppi & Aharonian (1999), only if the X-ray/γ-ray variations are consistent with being produced by a common electron ditribution, then it is possible to robustly estimate a BL Lac's intrinsic TeV spectrum from its emission at lower energies. [3] Contrasting measured versus intrinsic emission yields a determination of $\exp[-\tau_{\gamma\gamma}(E,\,z)]$, the energy-dependent absorption of the VHE emission coming from a source located at redshift z due to pair production with intervening EBL photons. Once $\tau_{\gamma\gamma}(E,\,z)$ is known, by assuming a specific cosmology one can derive the EBL photon number density: e.g., from $\tau_{\gamma\gamma}(E,\,z) = \int \int \int \sigma_{\gamma\gamma}(E,\,\epsilon,\theta)\,n_{\mathrm{EBL}}(\epsilon)\,\mathrm{d}\theta\,\mathrm{d}\epsilon\,\mathrm{d}\ell$ (see Eq. 2), if we have k values of $\tau_{\gamma\gamma}$ for k different values of E, by adopting a parametric form of $n_{\mathrm{EBL}}(\epsilon) = \sum_{0\,\mathrm{j}}^{\mathrm{k}} a_{\mathrm{j}}\epsilon^{\mathrm{j}}$ in principle we can solve for the k coefficients a_{j}.

Using SEDs from different HBLs and, for a given source, from different states of emission,

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[3] However, the electrons resulting from the interactions of the VHE photons and the EBL can upscatter EBL and CMB photons along the line of sight from the source to the observer, and these would also contribute to the observed SED (e.g., Venters, Pavlidou & Reyes 2009; Venters 2010; Inoue & Totani 2009; Kneiske & Mannheim 2008): if this contribution is significant, it could complicate the connections between the observations of sources in the various energy bands.

will improve the accuracy of the method by increasing the number of EBL measurements.

Setting $n_{\mathrm{EBL}}(\epsilon, z) = n_{\mathrm{EBL}}(\epsilon)(1 + z)^{\kappa}$, repeating the procedure at different redshift shells would allow us to estimate the EBL cosmic evolution rate parameter κ.

Clearly this approach could only have been used starting from the current epoch, because of the availability of *Fermi*/LAT data simultaneous with optical and X-ray data that allow us to substantially remove the degeneracy of the SSC model at low energies and hence to estimate, for the first time, the intrinsic TeV emission. The concomitant availability of simultaneous air Cherenkov data enables a measurement of the EBL opacity – albeit in a model-dependent way. We here propose using a homogeneous sample of same-emission sources to derive a coherent, unbiased picture of the EBL.

4.1. Best-fit procedure: χ^2 minimization

In order to fit the observed optical, X-ray and HE γ-ray flux with the SSC model, a χ^2 minimization is used. We vary the SSC model's 9 parameters by small logarithmic steps. If the variability timescale of the flux, t_{var}, is known, one can set $R \sim ct_{\mathrm{var}}\delta/(1 + z)$, so the free parameters are reduced to 8. We assume here $\gamma_{\mathrm{min}} = 1$: for a plasma with $n_{\mathrm{e}} \approx \mathcal{O}(10)\,\mathrm{cm}^{-3}$ and $B \approx \mathcal{O}(0.1)\,\mathrm{G}$ (as generally appropriate for TeV BL Lac jets: e.g., Ghisellini et al. 1998; Costamante & Ghisellini 2002; Finke, Dermer & Böttcher 2008), this approximately corresponds to the energy below which Coulomb losses exceed the synchrotron losses (e.g., Rephaeli 1979) and hence the electron spectrum bends over and no longer is power-law. However, in general γ_{min} should be left to vary – e.g., cases of a "narrow" Compton component require $\gamma_{\mathrm{min}} > 1$ (Tavecchio et al. 2010).

In order to reduce the run time of the code, the steps are adjusted in each run such that, a larger χ^2 is followed by larger steps.

5. Example: application to PKS 2155-304

We apply the procedure described in Sect. 4 to the simultaneous SED data set of PKS 2155-304 described in Aharonian et al. (2009). The data and resulting best-fit SSC model (from optical through HE γ-rays) are shown in Fig.(1). The extrapolation of the model into the VHE γ-ray range clearly lies below the observational H.E.S.S. data, progressively so with increasing energy. We attribute this effect to EBL attenuation, $F_{\mathrm{obs}}(E;\,z){=}F_{\mathrm{em}}(E;\,z)\,e^{-\tau_{\gamma\gamma}(E;\,z)}$. The corresponding values of $\tau_{\gamma\gamma}(E;\,z)$ for $E{=}0.23,\,0.44,\,0.88,\,1.70\,\mathrm{TeV}$ and a source redshift $z{=}0.116$ are, respectively, $\tau_{\gamma\gamma}=0.12,\,0.48,\,0.80$, and 0.87 .

We note that the SED analysis of Aharonian et al. (2009) was based on a slightly different SSC model, that involved a three-slope (as opposed to our two-slope) electron spectrum. This difference may lead to a somewhat different decreasing wing of the modeled Compton hump, and hence to a systematic difference in the derived $\tau_{\gamma\gamma}(E;\,z)$. That said, it's however interesting to note that the main parameters describing the plasma blob (B, δ, n_{e}) take on similar values in our best-fit analysis and in Aharonian et al. (2009). More generally, these parameters are quite similar to those deduced for other γ-ray BL Lac (see Tavecchio et al. 2010).

In Fig.(2) we compare our determination of $\tau_{\gamma\gamma}$ with some recent results (Franceschini et al. 2008; Gilmore et al. 2009; Kneiske et al. 2004; Stecker et al. 2006; Finke et al. 2010; Raue & Mazin 2008). Whereas our values are generally compatible with previously published constraints, we note that our values – that refer to a source redshift $z = 0.116$ – closely agree with the corresponding values of Franceschini et al. (2008; see their curve corresponding to $z = 0.10$), which are derived from galaxy number counts and hence represent the light contributed by the stellar populations of galaxies prior to the epoch corresponding to source redshift z_{s} – i.e., the minimum amount (i.e., the guaranteed level) of EBL (see also Malkan & Stecker 2001).
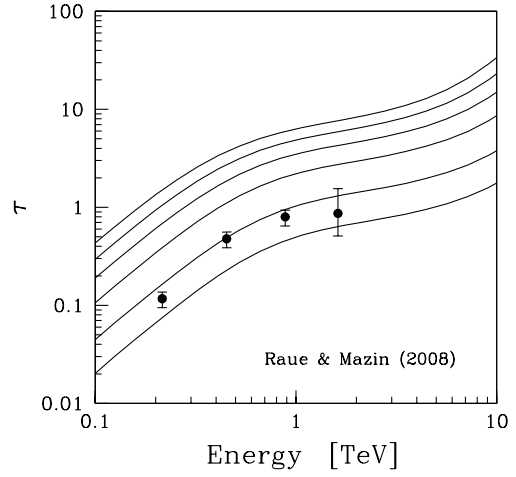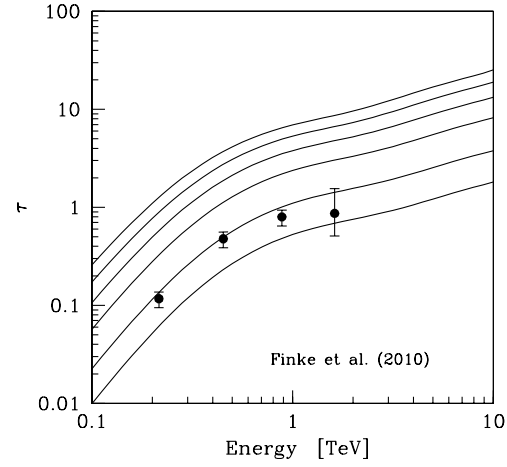
Franceschini et al. (2008)

Gilmore et al. (2009)

Kneiske et al. Low SFR (2004)

Stecker et al. (2006)

Fast evolution fit

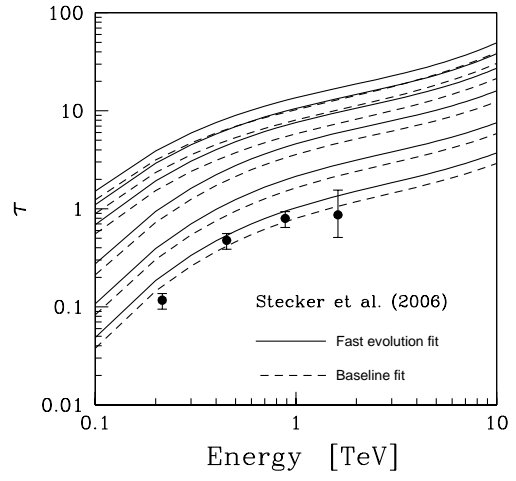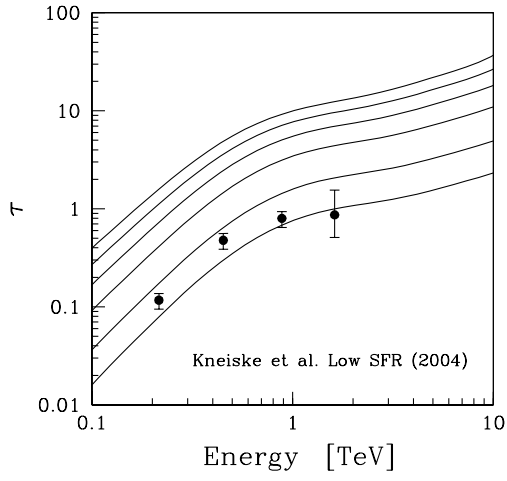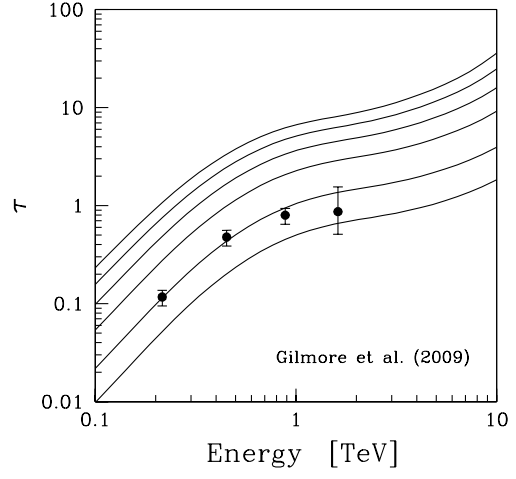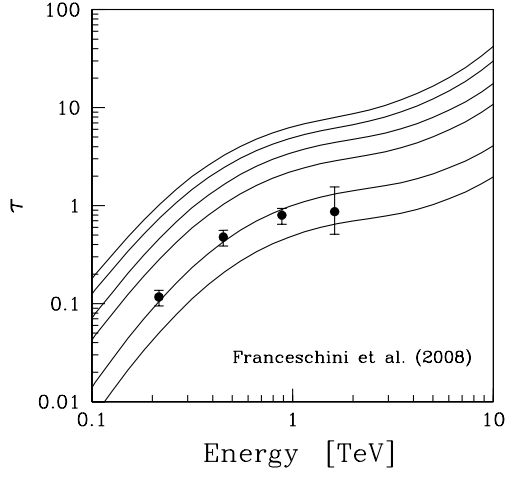Baseline fit

Finke et al. (2010)

Raue & Mazin (2008)

Fig. 2.— Measured values of $\tau_{\gamma\gamma}(E; z)$ for E=0.23, 0.44, 0.88, 1.70 TeV derived from comparing, for simultaneous observations of the high-frequency-peaked BL Lac object PKS 2155-304 ($z = 0.116$), the (EBL-affected) VHE γ-ray data with the eV-through-GeV best-fitting SSC model extrapolated into the TeV domain. Error bars on τ reflect those on H.E.S.S. data. The curves represent, for redshifts $z = 0.05$, 0.1, 0.2, 0.3, 0.4, 0.5 (from bottom up), the optical depth $\tau_{\gamma\gamma}(E)$ according to recent EBL calculations: a determination from galaxy counts (Franceschini et al. 2008: *top left*), two predictions based on a semi-analytic model of galaxy formation (Gilmore et al. 2009: *top right*) and a semi-empirical model of the EBL (Kneiske et al. 2004: *middle left*), a couple of predictions based on a galaxy formation model that includes two different galaxy evolution rates (Stecker et al. 2006: *middle right*), a galaxy formation model that takes into account the star formation rate, the stellar initial mass function, dust extinction, dust absorption and reradiation, main-sequence and post-main-sequence stars (Finke et al. 2010: *bottom left*), and a generic EBL density (not a complete model) that complies with all existing limits from direct and indirect methods (Raue & Mazin 2008: *bottom right*).

6. Conclusion

The method for measuring the EBL we have proposed in this paper is admittedly model-dependent. However, its only requirement is that all the sources used as background beamlights should have one same emission model. In the application proposed here, we have used a one-zone SSC model where the electron spectrum was a (smoothed) double power law applied to the SED of the HBL object PKS 2155-304. While this choice was encouraged by the current observational evidence that HBLs seem to have, with no exception, single-slope *Fermi*/LAT spectra, we could have as well adopted the choice (Aharonian et al. 2009) of a triple power law electron spectrum in our search for the best-fit SSC model of PKS 2155-304's SED. Should the latter electron distribution, or any other (e.g., curved) distribution, be shown to generally provide a better fit to high-quality *Fermi*/LAT spectra of HBLs, then that would become our choice. In general, what matters to the application of this method, is that *all* source SEDs be fit with one same SSC model.

Another assumption implicit in our method is that there is an absolute minimum in the χ^2 manifold of BL Lac emission modeling, and that our χ^2-minimization procedure is actually able to find it. Had that not been the case for PKS 2155-304, we would have checked whether the derived $\tau_{\gamma\gamma}$s are appreciably different for different model fits.

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